Chapter 3

SOLID WOOD—TIMBER ASSESSMENT MARKET MODEL (TAMM)

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Abstract. TAMM simulates behavior in the markets for solid wood products (lumber and wood-based panels) and sawtimber stumpage. TAMM is a spatial equilibrium model that projects market solutions one period at a time. Product demand is disaggregated into numerous end-use categories and recognizes contemporaneous price-based substitution between different classes of solid wood products. Product supply is derived from a restricted production function form to allow exogenous projection of product recovery factors. Capacity change over time is based on an accelerator approach adjusted for expected future returns. Sawtimber-stumpage supply relations derive from intertemporal profit and utility maximization objectives for industrial and nonindustrial private owners, respectively. Equilibrium solutions are found using a "net revenue maximization" approach constrained to meet conditions for a spatial equilibrium. A concluding literature review compares the TAMM structure with other approaches to modeling the solid wood sector.

Keywords: market model, sawnwood, wood-based panels, timber supply, spatial equilibrium

3.1 INTRODUCTION

TAMM was first developed for the 1980 RPA Timber Assessment (Adam and Haynes 1980). As described in Chapter 2 it was a spatial model of North American softwood lumber, plywood, and stumpage markets designed to provide long-term projections of price, consumption, and production trends. This chapter outlines the structure of the

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current version of TAMM used in the 2005 RPA Timber Assessment. TAMM focuses on solid wood products that include:

(1) Lumber or sawnwood of all types
(2) Panels, both structural (load-bearing panels including softwood plywood, and OSB) and nonstructural (hardwood plywood, particleboard and medium density fiberboard (MDF), hardboard, and insulation board)
(3) Miscellaneous products, including posts, poles, pilings, cooperage, and shakes and shingles

Within TAMM, production, consumption, prices, and interregional shipments of softwood lumber, softwood plywood, hardwood lumber, and OSB are endogenous. Import supplies of softwood lumber from all sources and OSB from Canada are also endogenous. Nonstructural panels and miscellaneous products consume less than 5% of the annual US timber harvest, and data on the cost and end-use characteristics of these products are limited. As a consequence, projections of volumes and prices of these products are developed using simplified methods outside the TAMM model (as described below). Imports and exports of softwood plywood and exports of softwood lumber and OSB, all involving small volumes, are treated as exogenous.

3.2 GENERAL TAMM STRUCTURE

TAMM is a static, partial spatial equilibrium model of the markets for solid wood products and sawtimber stumpage in the USA and Canada. It is, for the most part, a "static" model, in that it projects ahead only one period at a time and uses only past market information to generate expectations of future prices and volumes. In each (annual) time period, market balancing production, consumption, prices, and trade are determined by using equilibrium solution methods described by Takayama and Judge (1971) and Martin (1981). Between market solutions, production capacity is adjusted based on past prices, costs, and output; sawtimber inventory, a key factor in explaining private sawtimber supply, is updated for past harvest and growth by the ATLAS module (see Chap. 6).

3.3 MODELS OF SOLID WOOD MARKET COMPONENTS

In the USA, markets for solid wood products are characterized by large numbers of producers and buyers and are generally considered to be highly competitive. TAMM employs a classic competitive market structure in modeling these products. The specific markets and prices are those at the "mill level". The functions of wholesalers and other intermediaries in the distribution system are ignored. Supply volume is taken as mill production. Shipments from mills (as distinct from output) and mill inventories are ignored. Domestic demand is taken as apparent consumption (production + net trade). Product inventories held by consumers and unfilled orders at mills (as these represent expected future flows to consumers) are also ignored. Product demand is disaggregated to the demand regions described in Chapter 1 (Figure 1-4) and product supply is estimated from each supply region.

Sawtimber stumpage demand is a derived demand for input generated by producers of solid wood products. Sawtimber supply arises from two classes of price-sensitive private owners (forest industry [FI] and other private [NIPF]) and from two groups of public owners (national forests and other public) whose supplies are taken as independent of price. Sawlog flows among the supply assessment regions are limited and are not considered in TAMM. The price of logs delivered to the mill, which is the relevant factor price in product supply relations, is computed by adding logging and hauling costs to stumpage prices.

3.3.1 Demand for softwood lumber, softwood plywood, and OSB

TAMM is one of the few models of forest products markets that explicitly incorporates cross-price substitution terms in product demand relations when solving for market equilibrium. In most other models only the own-price terms appear. Demand for structural products is represented in TAMM using Spelter's (1984, 1985, 1992) technology diffusion models in which the fraction of the market captured by a particular product depends on a distributed lag in relative product prices. In Spelter's approach, the market for a given product (p) is divided into m_p end-use categories (denoted by the subscript i so that $i = 1, \ldots, m_p$). An end-use category is a specific application or

group of applications that uses solid wood product p as an input, e.g. new residential construction or furniture manufacturing. Rather than addressing the aggregate of all demands for p, consumption is subdivided into a set of smaller, more homogeneous demand components.

Total US demand for product p (Q_p) is the sum of its use across all end-uses (time subscripts are deleted except where essential):

$$Q_p = \sum_{i=1}^{m_p} Q_i^p \tag{3.1}$$

where

$$Q_i^p = M_i U_i^p \tag{3.2}$$

$$U_i^p = \bar{U}_i^p S_i^p \tag{3.3}$$

$$S_i^p = exp\left(-\frac{b_i^p}{T_t}\right) \tag{3.4}$$

$$T_t = T_{t-1} + \frac{P_{i,p,t} - P_{i,s,t}}{P_{s,t}} \tag{3.5}$$

in which

M_i^p is a measure of output of the ith end-use category (e.g. housing starts),

U_i^p is the consumption of product p per unit of output of end-use category i,

$\bar{U}_i^p$ is the maximum use of product p per unit of product i output,

S_i^p is the fraction of the maximum use of product p per unit of output of end-use category i,

$P_{i,p,t}$ and $P_{i,s,t}$ are prices of composite inputs using product p and its substitute (s) in end-use category i in period t (see discussion below), and

b_i^p is a parameter to be estimated.

For commodities that are in the "mature" phase of the product life cycle, such as softwood lumber and softwood plywood, $b_i^p < 0$; for commodities that have been more recently introduced into the market, such as OSB, $b_i^p > 0$. The cumulative relative price difference term, T, drives the substitution process. As the price difference between the solid wood product and its substitute rises (or persists over time),

T grows. For mature products like lumber or plywood, this would reduce S_i^p and hence the consumption of the solid wood product.

The prices employed in Spelter's model represent the costs of composite or aggregate inputs that employ the solid wood and substitute products (Chambers 1988).[1] Spelter also calls these composites "technologies". For example, the price of the lumber composite used in the framing of single-family dwellings would include the cost of lumber and all other inputs needed to produce one lineal meter of wall by means of a lumber-using technology in a single-family dwelling. Other composite inputs that do not use lumber, or use it in a different way, would represent substitute technologies. Because different types (grades and species) of lumber and plywood are employed in the wood-using technologies for the various end-uses categories, different price measures are incorporated in some of the end-use demand relations to best represent the grade of product actually employed. Softwood lumber is represented by the national all-softwood-lumber producer price index (PPI) (in most cases) or by the price of ponderosa pine boards in end-uses where board grades are most common. Plywood is represented by prices of southern pine and Douglas-fir species. Only a single OSB price is used. We link the lumber and plywood species/grade prices to their respective national PPIs using historical regressions.

TAMM includes demand equations for the end-use categories shown in Table 3-1 (together with the estimated year 2000 own-price elasticities of demand for each category). Most of the relations are of the form shown in equations (3.1–3.5) (see Spelter 1985 for discussion of other forms employed). Aggregate softwood lumber demand is highly inelastic with respect to its own price in the short term (annual elasticities average -0.1) as is softwood plywood (annual elasticities average -0.2). OSB demand elasticities have fallen steadily as it has captured a larger share of the structural panel market. In 1980 its own price elasticity was estimated to be -0.6, falling to -0.4 by 1990, and to -0.1 by 2000. Elasticities in many of the end-uses are extremely small for some products and zero in cases where the product did not enter one of the composite inputs. The model of equations (3.1–3.5) includes an explicit intertemporal adjustment process yielding, as would be

[1] Adams et al. (1992) provide an explicit derivation of factor demand expressed as factor use per unit of product output as in equation (3.2) for cost-minimizing producers using composite inputs.

Table 3-1. End-use categories of solid wood demand included in TAMM for softwood lumber, softwood plywood, and OSB and estimated year 2000 own price demand elasticities

End-use category	Softwood lumber	Softwood plywood	OSB	End-use output measure
Single-family dwellings:				
Framing	−.02			Floor area single-family housing starts
Sheathing: total	−.04			Floor area single-family housing starts
Roof sheathing		−.07	−.07	Floor area single-family housing starts
Floor sheathing		−.09	−.08	Floor area single-family housing starts
Wall sheathing		−.16	−.02	Floor area single-family housing starts
Siding		−.03	−.05	Floor area single-family housing starts
Millwork	−.06	−.02		Floor area single-family housing starts
Basement	−.25			Floor area single-family housing starts
Multifamily dwellings: total	−.02	−.07	−.07	Floor area multifamily housing starts
Mobile homes: total	−.04	−.22	−.01	Floor area mobile homes
Residential repair and alteration	[a]	−.08	−.10	Real expenditures on residential repair and alteration
Nonresidential:				Real value of nonresidential construction
Building	[a]	−.11	−.07	For buildings
Farm	[a]	−.07	−.07	For farms
Utilities	[a]			For utilities
Miscellaneous	[a]	−.08	−.05	For all other
Shipping	−.10	−.11	−.10	Index of manufacturing production
Manufacturing	−.04	−.05	−.18	Index of manufacturing production
Pallets	[a]			Softwood pallet production
Furniture	[a]			Index of manufacturing production for furniture
Ties	[a]			Total softwood tie production
Other	−1.60	[a]	−.07	
Total	−.10	−.24	−.07	

[a] Value less than −0.01.

expected, more elastic response for longer adjustment periods. Thus, for the aggregate of all end-uses, demand elasticity rises by a factor of 2 to 3 over a 5-year period in the face of a sustained own-price change.

Using Spelter's original equation form for the evolving market share (3.4) leads to fairly complex demand relations in the spatial equilibrium solution process. To simplify the model, a linear approximation of the aggregate national level demand functions is developed in each year of the simulation at a set of projected product prices. Adding up quantities across all end-uses as in (3.1), national demand relations for the products can be written in general form as:

$$Q_p = Q_p(p_L, p_P, p_O, Z) for\ p = L, P, O \tag{3.6}$$

where

- p_p are the national prices of lumber (L), plywood (P), and OSB (O), respectively, and
- Z is a set of exogenous demand shifters, including prices of nonwood substitutes.

Setting the exogenous variables to their current period values, equation (3.6) is linearized using numerical methods to the form:

$$\begin{aligned} Q_L &= a_L + a_{L,L}p_L + a_{P,L}p_P + a_{O,L}p_O \\ Q_P &= a_P + a_{L,P}p_L + a_{P,P}p_P + a_{O,P}p_O \\ Q_O &= a_O + a_{L,O}p_L + a_{P,O}p_P + a_{O,O}p_O \end{aligned} \tag{3.7}$$

To develop estimates of regional demand equations, regional delivered product prices ($p_{p,r}$) are linked to the national prices (p_L, p_P, and p_O) by simple historical linear regressions of the form:

$$p_{p,r} = b_{0,p,r} + b_{1,p,r}p_p \quad for\ p = L, P, and\ O\ and\ r = 1, \ldots, n_R \tag{3.8}$$

where

- $p_{p,r}$ is the price of product p in region r, and
- n_R is the number of US demand regions.

Regional shares of national consumption for product p are derived from exogenous projections of regional per capita consumption trends and regional population as:

$$s_{p,r} = \left(\frac{Q}{N}\right)_{p,r} N_{p,r} \tag{3.9}$$

and

$$Q_{p,r} = s_{p,r} Q_p \tag{3.10}$$

where

$s_{p,r}$ is region r's share of national consumption of product p,

$(Q/N)_{p,r}$ is projected per capita consumption of product p in region r,

$N_{p,r}$ is projected population in region r, and

$Q_{p,r}$ is consumption of product p in region r.

Substituting (3.7–3.8) into (3.10), regional demand equations can be written as:

$$Q_{p,r} = s_{p,r} \left[a_p + \sum_{k=L}^{O} a_{k,p} \left(-\frac{b_{0,k,r}}{b_{1,k,r}} + \frac{p_{k,r}}{b_{1,k,r}} \right) \right] \tag{3.11}$$

In this approach, the relation of the regional and national elasticities is proportional to the ratio of regional delivered price/national price:

$$\begin{aligned} e_{p,r} &= \frac{\partial Q_{p,r}}{\partial p_{p,r}} \frac{p_{p,r}}{Q_{p,r}} = s_{p,r} \left[\frac{a_{p,p}}{b_{1,p,r}} \right] \frac{p_{p,r}}{Q_{p,r}} = \left(\frac{p_{p,r}}{p_p b_{1,p,r}} \right) \left(\frac{\partial Q_p}{\partial p_p} \frac{p_p}{Q_p} \right) \\ &= \left(\frac{p_{p,r}}{p_p b_{1,p,r}} \right) e_p \end{aligned} \tag{3.12}$$

where

$e_{p,r}$ is the region r own price demand elasticity for product p, and

e_p is the national own price demand elasticity for product p.

Lumber and panels are primarily producer goods used as inputs to the production of end-use products such as housing or furniture. Competitive end-use producers would determine the optimal levels of lumber, plywood, and all other inputs in the profit maximization process. Assuming production functions in these many end-uses that meet the usual curvature conditions, the derived demands for solid wood and other factors obey the usual symmetry conditions—the partial derivative of the demand for input i with respect to the price of input j is equal to the partial derivative of the demand for input j with respect to the price of input i (see, e.g. p131 in Chambers 1988). Spelter's

model, and many other studies of demand for forest products, focuses exclusively on the derived demand relations for individual solid wood products. Demands for lumber are estimated independent of demands for plywood or OSB. As a consequence, symmetry is not imposed. For example, the partial derivative of the demand for softwood lumber with respect to the price of softwood plywood will generally not equal the partial derivative of the demand for softwood plywood with respect to the softwood lumber price in any given end-use where lumber and plywood are potential substitute inputs. The lack of cross-price symmetry will be true as well for equations (3.7) and (3.11). This outcome has important implications for the methods used to solve the spatial market equilibrium, since the demand equations will not be integrable with respect to the wood product prices (see pp107–128 in Takayama and Judge 1971). Note that this is not an issue in (most) studies that ignore cross-price effects among wood products in demand.

3.3.2 Demand for hardwood lumber

The demand system for hardwood lumber also focuses on mill-level markets and splits consumption into eight end-use categories: furniture, flooring, millwork, ties, pallets, mining, containers and dunnage, and miscellaneous (all other categories). Use in mining and containers and dunnage is relatively modest and is projected outside the model. Demand relations for the remaining six categories employ a simple "end-use factor" form as described by Adams et al. (1992):

$$\left(\frac{D_i}{A_i}\right)_t = f\left(\frac{P^C_{L,i}}{P^C_{S,i}}, t\right) \tag{3.13}$$

where

D_i is hardwood lumber consumption in end-use category (industry) i;

A_i is the level of output (or activity) in end-use category i;

$P^C_{L,i}, P^C_{S,i}$ are the prices of hardwood lumber and substitute composite products used in end-use industry i; and

t is a time trend representing technological change in the end-use industry.

Table 3-2. End-use categories in TAMM for hardwood lumber and estimated own-price demand elasticities

End-use	Elasticity of demand	End-use activity measure
Furniture	−0.7	IIP-furniture
Flooring	−1.9	Floor area of single-family homes
Millwork	−1.0	IIP-millwork
Ties	−0.1	Total US tie production
Pallets	−0.3	Total US pallet production
Miscellaneous	−1.2	IIP

IIP = Industrial production index.

Prices of the composite products (see discussion in Sect. 3.3.1) include, wherever possible, both materials (such as lumber or substitutes) and labor. Estimated lumber price elasticities are shown in Table 3-2. Unlike the softwood and OSB markets, we do not disaggregate hardwood demand by geographic region, due to lack of reliable data on the actual geographic distribution of hardwood lumber shipments. Hardwood lumber is a substitute for some types of softwood lumber in certain applications (primarily pallets). Since modeling focuses on the derived demands for the specific lumber species groups and not on the end-use industries, issues of asymmetry of cross-price partials in the demand equations arise here just as in the case of softwood lumber.

3.3.3 Product supply relations and capacity adjustment

TAMM includes solid wood supply relations for softwood lumber, softwood plywood, OSB, and hardwood lumber. Softwood lumber supply regions include all domestic regions, three regions in Canada and one “off-shore” region comprising all rest-of-world suppliers. US lumber exports are small and treated as exogenous. Softwood plywood supply is price sensitive only in US regions, and imports and exports are exogenous. OSB supply relations are developed for US regions and one “all Canada” region. Other imports and all exports of OSB are exogenous. Hardwood lumber trade is also exogenous.

3.3.3.1 North American supply relations

In TAMM, trends in the technology of wood products processing and logging have traditionally been treated by using specific scenarios of future technical developments. Wood-use efficiency in milling is represented by "product recovery factors": product output/log input ratios (e.g. cubic meters of lumber output per cubic meter log input). To explicitly incorporate these external projections in the product supply relations, we assume a constrained form of the production process. Product output is obtained in fixed proportions to log input (the product recovery factor linkage), but in variable proportions to all other factors. Assuming quasi-fixed capital inputs, the production function for a specific product would appear as:

$$Q = \min(r_W W, f(X_1, X_2, \ldots, X_n, K)) \tag{3.14}$$

where

Q is output,

r_W is the product recovery factor for logs (lumber output/log input),

W is log input,

X_i for $i = 1, \ldots, n$ are nonwood variable inputs, and

K is capital.

The function f can be viewed as an aggregator function for the other inputs and the two groups of factors, W and $(X_1, \ldots, X_n, K)$, are weakly separable.

If $p = \{p_W, (p_1, \ldots, p_n)\}$ is the set of prices of wood and all other variable inputs, the cost function for the production function in (3.14) can be shown to be:

$$C(p, Q) = C_W(p_W, Q) + C_O(p_1, \ldots, p_n, Q, K) \tag{3.15}$$

where C_W is the cost function for the wood input and is

$$C_W(p_W, Q) = p_W \frac{Q}{r_W} \tag{3.16}$$

and C_O is the cost function for all other inputs. Chambers (1988) shows that the profit function can be written as:

$$\Pi(p, P, K, Q^*) = PQ^* - C_W(p_W, Q^*) - C_O(p_1, \ldots, p_n, Q^*, K) \tag{3.17}$$

where

Q^* is optimal (profit maximizing) output

Thus the supply function can be found by Hotelling's lemma from:

$$\frac{\partial \Pi}{\partial P} = P\frac{\partial Q^*}{\partial P} + Q^* - \frac{\partial C_W}{\partial Q^*}\frac{\partial Q^*}{\partial P} - \frac{\partial C_O}{\partial Q^*}\frac{\partial Q^*}{\partial P} = Q^* \tag{3.18}$$

or

$$P = \frac{\partial C_W}{\partial Q^*} + \frac{\partial C_O}{\partial Q^*} \tag{3.19}$$

If the profit and cost functions are normalized by the price of one of the inputs (see discussion below) and if C_O in equation (3.15) can be represented by the (normalized, restricted) quadratic form, then:

$$\begin{aligned} C_O\left(p_1, \ldots, p_n, Q, K\right) &= b_0 + \sum_i b_i p_i + \frac{1}{2}\sum_i b_{ii} p_i^2 + \sum_i b_{iK} p_i K \\ &\quad + \sum_i b_{iQ} p_i Q + b_Q Q + b_K K + \frac{1}{2} b_{KK} K^2 \\ &\quad + \frac{1}{2} b_{QQ} Q^2 + b_{KQ} KQ \end{aligned} \tag{3.20}$$

Using (3.16), (3.18), and (3.20), the supply function can be written as:

$$Q^* = -\frac{b_Q}{b_{QQ}} + \frac{1}{b_{QQ}}\left[P - \frac{p_W}{r_W}\right] - \sum_i \frac{b_{iQ}}{b_{QQ}} p_i - \frac{b_{KQ}}{b_{QQ}} K \tag{3.21}$$

or

$$Q^* = a_0 + a_P\left[P - \frac{p_W}{r_W}\right] + \sum_i a_i p_i + a_K K \tag{3.22}$$

Residues in lumber and plywood production are assumed to be generated in fixed proportion to output. Residue revenues per unit output are added to product price in the term in brackets in (3.22) which becomes $\left[P - \frac{p_W}{r_W} + p_{residues}\right]$. Nonwood variable factors are separated into two groups: a first, readily measurable set, comprising direct labor, energy, and certain other materials and services, and a second set of "all other variable inputs". The first group is treated as a composite input, and its aggregate price enters (3.22) as the only element of the summation of the p_i, called p_{nwc}. The second group is also treated as a composite input and taken as the numeraire input used to normalize all other prices. Its price is assumed to be measured by

the all commodity producer price index. The resulting product supply equations have the form:

$$Q = a_0 + a_P \left[\tilde{P} - \frac{\tilde{p}_W}{r_W} + \tilde{p}_{residue} \right] + a_n \tilde{p}_{nwc} + a_K K \qquad (3.23)$$

where $\tilde{p}$ denotes a price normalized by the price of all other variable inputs.

Capital (K) is the aggregate of all buildings, machinery, and production organization methods used in the milling process. Studies of production behavior typically construct some real value measure of the stock of structures and machinery to represent capital input, assuming capital services are proportional to stock. In TAMM, capital is measured by an estimate of output capacity, which can be viewed as the maximum service level obtainable from the capital stock. Capacity data are derived from a combination of estimates published by industry associations and from production, price, and cost data using a modified form of the "trends through peaks" method.[2]

Key elasticity results are shown in Table 3-3. The OSB equations were estimated for the USA and Canada as aggregates. Direct estimation of regional OSB supply equations in the USA was not attempted given the limited number of time series observations. Regional equations for the USA were derived by scaling the national relations using regional proportions of total capacity at the start of each period. Thus US regional and national OSB supply elasticities are identical. Canadian OSB supply was not disaggregated by region. Production is treated as if it all originated in eastern Canada.

3.3.3.2 Capacity adjustment

Capacity is projected using a two-stage process:

(1) Initial estimates of capacity change, or net investment in capacity, are derived from a set of regional adjustment equations. These relations employ an accelerator structure in which change in capacity is a distributed lag in past changes in output (see Chap. 8 in Evans 1969, for a discussion of the many forms of the accelerator model). We employ both finite lag structures

[2] In the usual "trends through peaks" method, capacity is identified, as the name implies, by simple straight line trends through peak output levels. Our approach uses output, prices, and operating margin (gross revenue less variable costs) to identify key points on the capacity time path. Periods during which output approaches capacity are identified by peaks in the basic output series and also by peaks in price and operating margin. Just as critical are the points where capacity expansion is reinitiated after periods of stability or decline. Here, again, increases in operating margin, even with a continued decline in output, help to identify such points.

Table 3-3. Solid wood product supply elasticities for the USA and Canada

Product and region	Real lumber price	Real nonsawlog costs	Capacity
Softwood lumber:			
Pacific Northwest West	0.611	−0.157	1.144
Pacific Northwest East	0.345	−0.108	1.206
Pacific Southwest	1.481	−0.549	1.730
Northern Rockies	0.502	−0.420	1.055
Southern Rockies	0.307	−1.151	1.221
North Central	0.825	−0.158	1.033
Northeast	0.277	−0.053	1.618
South Central	0.561	−0.506	0.935
Southeast	0.766	−0.388	0.658
Coastal BC	0.995	−0.521	1.122
Canada Interior	0.433	−0.235	1.130
Canada East	0.355	−0.149	1.093
Softwood plywood:			
Pacific Northwest West	1.013	−0.752	1.268
Pacific Northwest East	0.910	−0.810	0.989
Northern Rockies	0.910	−0.170	0.964
South Central	0.811	−1.190	0.962
Southeast	0.529	−0.895	0.957
OSB:			
USA	0.225	−0.116[a]	1.118
Canada	0.210	−0.126[a]	1.177
Hardwood lumber:			
North Central	0.207	−0.092	0.975
Northeast	0.255	−0.146	1.121
South Central	0.270	−0.109	1.041
Southeast	0.134	−0.054	0.829

[a] OSB costs include wood.

using the polynomial distributed lag approach and exponential, Koyck-type schemes. Forms of the final equations vary across regions depending on which approach provided the best explanation of historical behavior, but the basic structure for region r in period t is:

$$\Delta K_{1,r,t} = \sum_i w_{i,r} \Delta Q_{t-i,r} \tag{3.24}$$

where

$\Delta K_{1,r,t}$ is the first step estimate of capacity change for region r in period t.

$\Delta Q_{t-i,r}$ is the change in output in period $t-1$ in region r, and

$w_{i,r}$ are the distributed lag weights.

(2) Projections from the capacity change equations are then adjusted for anticipated "operating margin" performance, where operating margin is defined as product price plus residue revenues less variable costs (wood and nonwood). A naive estimate of expected operating margin is developed from the average of the past three years' margin. This is compared to a "target" or minimum acceptable margin. If the expected margin is higher than the target, projected capacity increments (from 3.24) are increased or projected decrements are reduced by preset fractions. If the expected margin is below the target, decrements are increased or increments are reduced. An upper bound on the absolute level of capacity change is also imposed. Because our basic cost and price data differ from region to region in terms of the breadth and specificity of costs and products covered, and because the quality mix of products varies across regions, we vary margin targets by region. The process can be represented as:

$$\bar{\Pi}_{t,r} = \frac{1}{3}\sum_{i=1}^{3}\left[P_{t-i} + p_{residue,t-i} - \frac{p_{w,t-i}}{r_{w,t-i}} - p_{nwc,t-i}\right]$$

$$\Delta K_{2,r,t} = \begin{array}{lcl} (1+\delta_r)\,\Delta K_{1,r,t} & \multirow{2}{*}{if} & \bar{\Pi}_{t,r} > \Pi_r^T \\ (1-\delta_r)\,\Delta K_{1,r,t} & & \bar{\Pi}_{t,r} < \Pi_r^T \end{array} \tag{3.25}$$

$$\Delta K_{2,r,t} \leq \Delta K_{MAX,r}$$

where

$\bar{\Pi}_{t,r}$ is the past average operating margin, taken as an expectation of future margin,

$\Delta K_{2,r,t}$ is the second step estimate of capacity change in region r for period t,

Π_r^T is the target margin for region r,

δ_r is preset adjustment fraction, and

$\Delta K_{MAX,r}$ is an upper bound on current period capacity expansion in region r.

Like investment relations derived from neoclassical intertemporal production theory and Tobin's q, the motivation for this approach

is to adjust investment for anticipated returns.[3] If the target margin is viewed as an estimate of the (annualized) unit cost of new capacity, the approach would be similar to the Tobin q method described in Chapter 4 for the pulp and paper sector. It would be a rearrangement of equation 9 in Zhang and Buongiorno's 1993 paper. It is also similar to the method of Trømborg and Solberg (1995) in the Norwegian NTM II model, which examines the difference: price–variable costs–unit capacity cost, raising capacity if it is positive and lowering it if negative. The critical effect in the model is to mimic the results of competition, allowing capacity to migrate into (or out of) regions which realize high (or deficient) margins over multiyear periods.

3.3.3.3 Offshore softwood lumber supply

Over the last decade growing volumes of US softwood lumber imports have been derived from countries other than Canada, including Western Europe, Latin America, and Pacific Rim regions. Given the diversity and changing composition of countries involved in this trade, their supplies were aggregated into a single "off-shore" softwood lumber supply relation or "rest-of-world" supply.[4] Based on past growth and volatility, the offshore supply relation was judgmentally assigned an own-price elasticity of 1.5. Given the short period of experience with these flows (offshore supply grew from 0.8% of US consumption in 1995 to 4.2% by 2004), their future development is modeled on a scenario basis with exogenous shifts in their aggregate supply relation over time.

3.3.3.4 Softwood lumber trade restrictions

Over the period of development of TAMM, trade restrictions on the importation of Canadian softwood lumber to the USA have taken many forms. Kennedy (2006) offers a useful summary of the "softwood lumber trade dispute" over the last 20 years. Most recently the countries agreed on a "tariff/optional quota" system linked to the level of softwood lumber prices in US markets. When the US price indicator is above a threshold, there are no taxes or quotas. When it is below the threshold, provinces in Canada can opt for either an

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[3] See Hayashi (1982) for discussion of the neoclassical model and Tobin's q.

[4] During 2004 and 2005 the largest non-Canadian exporter of softwood lumber to the US was Germany which accounted for about 25% of the off-shore volume. The remaining 75% came from a large number of countries, no one of which accounted for more than 10–12% of the total.

export tariff (ranging from 5% to 15%) or a quota based on historical provincial shares of US imports with a reduced tariff. Given the complexity of this system and the apparent ability of provinces to switch between tariff and quota regulation over time, the 2005 RPA Timber Assessment base case assumes a simple fixed tariff of 10% (at the midpoint of the tariff range) on all shipments as representative of the "average" restriction.

3.3.4 Demand for logs and stumpage

As noted above, solid wood production technology in TAMM is assumed to be fixed proportions for wood input. Demand for log input for product p in region r is therefore:

$$d_{p,r} = \frac{Q_{p,r}}{r_{w,p,r}} \tag{3.26}$$

which varies with log price, p_w, as $Q_{p,r}$, product output, varies. For OSB, which uses a mix of species, roundwood, and residues in its inputs, the softwood–hardwood and roundwood–residue proportions are prespecified as part of the recovery process.

3.3.5 Sawtimber stumpage supply

TAMM includes both public and private sawtimber-stumpage supply in the USA and delivered sawlog costs in Canada. Pulpwood supply equations for the USA and Canada are included in the pulpwood model discussed in Chapter 4. In the eastern USA, the supplies of sawtimber and pulpwood stumpage are interdependent in sawtimber and pulpwood prices, reflecting the output mix decisions faced by private owners in those regions.

3.3.5.1 Public timber supply

Since 1990 timber cut from public lands has fallen from roughly 20% of total US harvest to about 8%, as a result of changes in management objectives on federal and some nonfederal public ownerships. Most (67% in 2001) of the public lands and associated harvest volume is in the Western regions. On almost all classes of public forest land, the volumes of timber offered for sale each year are determined largely through policy processes that do not involve timber prices. The amount of timber offered for sale that is actually purchased by private operators and, once purchased, the rate at which it is harvested

both depend in part on prices (see Adams and Haynes (1989) for a detailed treatment of this mechanism on national forests). But given the small volumes involved in recent years (and the relatively short contract periods for these sales), we treat public harvest as exogenous. Harvests vary over time according to scenarios of future public timber management policies.

3.3.5.2 Private timber supply

Private timberland owners are divided into FI and NIPF groups based on integration of the owner with wood or fiber products processing facilities. When TAMM was first developed in the late 1970s, this split was thought to provide a rough distinction between the broad objectives for holding timberland as well: FI owners being primarily concerned with present value maximization, while the objectives of NIPF owners might include an array of nontimber or amenity concerns in addition to wealth maximization. In the last 15 years, however, large areas of FI ownership have been sold or transferred to a third "industry-like" group comprised of a growing number of nonintegrated owners such as TIMOs and REITs that hold timberland as an investment but do not own processing facilities. This group is generally thought to behave more like FI owners in both its timber harvest responses (to price and other market changes) and silvicultural investments, although there has been only a limited time span in which to actually observe these traits. Lumping this group with NIPF owners, on the other hand, is clearly inappropriate. As of 2006, it is estimated that some 15.7 million ha of FI land has been transferred to TIMOs and REITs out of a total industrial land base of 26.1 million ha. If these areas are roughly representative, about two-thirds of the former FI land base has been shifted to this new owner class.

Unfortunately, little data on timber harvest and timber inventory using this more detailed three-owner categorization are available. Few states or regions actually report private timber harvest, and many that do continue to use the older ownership classification in which nonintegrated owners are classed as nonindustrial. Further, reported national inventory statistics (Smith et al. 2004) also use the older two group definitions. As a consequence, TAMM's timber supply relations for the US use the older groupings as well, although there are some mitigating conditions that may lessen the problems associated with this aggregation. Much of the major land shift from FI to industry-like occurred since the effective dates of the timber inventories used in

ATLAS, so our projections will still treat these areas as "industrial" lands (being managed primarily for timber production). And in the South, where this ownership change first developed, it was possible to split the inventory data (although not the harvest) into roughly the desired three-owner classification. As a result, the timber supply behavior of the Southern industry-like group reflects the general price responses of the NIPF class, but its silvicultural investment behavior mimics the FI group.

As noted above, we assume that FI owners act as present value maximizers. Following Ovaskainen (1992), a simple two-period representation of the industrial owner's intertemporal harvest optimization problem would be:

$$\begin{aligned} &\underset{\{C_t\}}{max} \quad P_1C_1 + (1+r)^{-1}P_2C_2 \\ &subject\ to: \\ &C_2 = I_0 + g(I_0 - C_1) - C_1 \end{aligned} \tag{3.27}$$

where

C_t is harvest in period t,

P_t is stumpage price in period t,

I_0 is initial inventory,

r is the discount rate, and

g is the growth function of residual inventory, $g' > 0, g'' < 0$.

Assuming constant future price expectations ($P_2 = P_1$), the formulation in equations (3.27) yields a current (first) period timber harvest function that depends on price, inventory, and the discount rate:

$$C = C(P, I, r) \tag{3.28}$$

Comparative statics indicate that $C_P > 0, C_I > 0$, and $C_r > 0$.

NIPF owners are assumed to be intertemporal utility maximizers who derive benefits from (1) the consumption of goods purchased with income earned either selling timber or from other "nonforest" sources, and (2) the standing stock of timber itself. Again following Ovaskainen (1992), a simple, two-period version of the typical owner's intertemporal maximization problem can be written as:

$$max \quad U(G_1) + V(I_1) + (1+\delta)^{-1}\{U(G_2) + V(I_2)\}$$

$\{G_1, C_i\}$

subject to:

$$\begin{aligned} I_1 &= I_0 - C_1 \\ I_2 &= I_1 + g(I_1) - C_2 \\ G_1 &= P_1C_1 + M - S \\ G_2 &= P_2C_2 + (1+r)S \end{aligned} \tag{3.29}$$

where

$U(.)$ and $V(.)$ are the owner's utility functions for commodities and amenities, respectively, in a given period,

C_i are harvests in periods 1 and 2,

I_i are inventories at times 0 (given), 1 and 2,

P_i are exogenous prices of stumpage in periods 1 and 2,

r is the exogenous earnings rate on savings,

δ is the owner's rate of time preference,

M is exogenous nonforest income,

S is period 1 savings, and

G_i is consumption of commodities in periods 1 and 2.

This formulation assumes an additively separable utility function both over time and between commodities and non-commodities.[5] The utility functions for commodities, U, and noncommodities, V, are assumed to display positive but diminishing marginal utilities so that V' and $U' > 0$, and V'' and $U'' < 0$. Noncommodity benefits are assumed to derive from the stock of timber, I_i, in each period after harvest. Only G_1 and the C_i need be considered in the optimization, since S can be replaced by a function of C_1 and G_1, G_2 is then a function of G_1 and the C_i and the inventory terms depend only on the $C_{i.}$ Finally, the growth function, g, has the same properties as assumed in the industrial case. Solution of the problem in relations (3.29) yields a first-period harvest function that depends on the P_i, r, M, initial inventory (I), and the unobservable (δ). Dropping the

[5] In this case the function is strongly separable in consumption and investments in the two time periods. Aggregate utility over the full two-period time horizon is obtained by summing contributions from the two periods.

latter and assuming constant future price expectations ($P_2 = P_1$), we have:[6]

$$C = C(P, I, M, r) \tag{3.30}$$

We implement these theoretical developments by using a partial adjustment form of the supply relation in which the elasticity of harvest with respect to inventory is constrained to unity for both owners. We also assume that owners in the East face decisions about the mix of harvest between sawtimber and pulpwood and so include both pulpwood and sawtimber stumpage prices:

$$\begin{aligned} \left(\frac{C}{I}\right)_{S,I} &= c_{S,I}\left[P_S, P_P, r, \left(\tfrac{C}{I}\right)_{S,I,t-1}\right] \qquad \text{for FI owners} \\ \left(\frac{C}{I}\right)_{S,N} &= c_{S,N}\left[P_S, P_P, r, M, \left(\tfrac{C}{I}\right)_{S,N,t-1}\right] \quad \text{for NIPF owners} \end{aligned} \tag{3.31}$$

and the functions $c_{S,I}$ and $c_{S,N}$ are linear in coefficients. The inventory elasticity restriction in this form limits the generality of our results but resolves significant collinearity problems between the inventory, price, interest rate, and income terms. The forms in (3.31) have also proven to be quite powerful in explaining historical harvest behavior across all regions. Stumpage price elasticity results are shown in Table 3-4.

In Canada, Crown lands managed by the provinces are the primary sources of timber supply. In general, harvest levels are determined by the annual allowable cut (AAC), but there are numerous exceptions to this limit, and the methods of computing the AAC vary substantially across the provinces (Canadian Council of Forest Ministers 2005).[7] TAMM employs a highly simplified scheme for modeling the cost of wood delivered to Canadian lumber mills. A log-linear regression is used to link historical delivered wood cost and the volume of wood consumed at lumber mills in each of the three Canadian regions. In projections, these relations are shifted according to externally generated scenarios of future Canadian allowable-cut policies and cost developments. The Canadian relations enter TAMM in the same way

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[6] Comparative statics using the first order conditions from optimization of (3.29) reveal that $C_M < 0$ and $C_r \geq 0$ but the expected signs of C_P and C_I can not be unambiguously determined.

[7] Also see the national forestry database program at http://nfdp.ccfm.org/compendium/harvest/ and the associated link to the wood supply document.

Table 3-4. Elasticities of private softwood and hardwood stumpage supply with respect to major determinants

Region	Owner[a]	Sawtimber price	Pulpwood price	Real interest rate	Real disposable income/ person	Lagged cut/inv ratio	Inventory
Softwood sawtimber supply:							
Pacific Northwest West	FI	0.183		0.023		0.632	1
Pacific Northwest West	OP	0.310		0.051		0.665	1
Pacific Northwest East	FI	0.409				0.238	1
Pacific Northwest East	OP	0.638		0.047		0.585	1
Pacific Southwest	FI	0.317				0.311	1
Pacific Southwest	OP	0.306			−2.853		1
Northern Rockies	FI	0.126		0.040		0.515	1
Northern Rockies	OP	0.175				0.115	1
Southern Rockies	FI	0.279				0.465	1
Southern Rockies	OP	0.516			−4.212		1
North Central	FI	0.590	−0.077	0.035		0.573	1
North Central	OP	0.385	−0.246	0.026	−0.808	0.897	1
Northeast	FI	0.683	−0.797			0.814	1
Northeast	OP	0.986		0.000[b]	−0.624	0.841	1
South Central	FI	0.193	−0.294	0.046		0.807	1
South Central	OP	0.131	−0.094	0.044	−0.127	0.935	1
Southeast	FI	0.152	−0.114	0.060		0.923	1
Southeast	OP	0.258	−0.463	0.053	−0.272	0.898	1
Coastal BC[c]		0.367					
Canadian Interior[c]		0.656					
Canada East[c]		0.112					
Softwood pulpwood supply:							
North Central	FI	−0.593	0.571				1
North Central	OP		0.373	0.005	−0.938		1
Northeast	FI		0.278			0.568	1
Northeast	OP	0.000	0.423		−0.276	0.914	1
South Central	FI		0.214			0.347	1
South Central	OP		0.314			0.668	1
Southeast	FI		0.521	0.021		0.538	1
Southeast	OP	−0.273	0.291		−0.101		1
Hardwood sawtimber supply:							
North Central	FI	0.434	−0.322	0.033		0.962	1
North Central	OP	0.242	−0.238	0.048		0.737	1
Northeast	FI	0.178	−0.089	0.046		0.994	1
Northeast	OP	0.184			−0.459	0.733	1
South Central	FI	0.490	−0.187	0.044		0.616	1
South Central	OP	0.478	0.124	0.042		0.643	1
Southeast	FI	0.252	0.033	0.031		0.738	1
Southeast	OP	0.407	0.195	0.057		0.768	1

Table 3-4. Continued

Region	Owner[a]	Sawtimber price	Pulpwood price	Real interest rate	Real disposable income/person	Lagged cut/inv ratio	Inventory
Hardwood pulpwood supply:							
North Central	FI	0.764	0.789	0.099		0.420	1
North Central	OP	−0.545	0.395			0.450	1
Northeast	FI	−0.080	0.258	0.007		1.161	1
Northeast	OP	0.201	0.375		−0.327	0.451	1
South Central	FI		0.579	0.112			1
South Central	OP		0.259			0.559	1
Southeast	FI	0.277	0.412	0.071			1
Southeast	OP		0.126	0.042		0.648	1

[a] FI is forest industry, OP is other private, also referred to as nonindustrial private (NIPF).
[b] 0.000 elasticity less than 0.001.
[c] Canadian relations are for delivered wood costs in deflated Canadian dollars.

as the private US timber supply equations, and Canadian delivered-wood cost is determined simultaneously with other endogenous prices and quantities. A summary of elasticities for delivered sawlog supply for the Canadian regions is also given in Table 3-4.

3.3.6 Nonstructural panels

Consumption, production, and prices of nonstructural panels (hardwood plywood, particleboard-medium density fiberboard, hardboard, and insulation board) are projected outside of TAMM. Trend and judgmental estimates of future consumption per unit of end-use activity are developed and multiplied by projected end-use levels to estimate consumption. Trended net trade is deducted to estimate domestic production. Real prices, which have been stable to declining in the USA for all of these products over the last 25 years, are projected to remain constant over the projection period. Within TAMM, the wood requirements from domestic production are computed from recovery factors. Estimates of the mix of roundwood and residues and of softwood and hardwood species are used in each product category. While US production and consumption of some categories of nonstructural panels have shown rapid growth over the last two decades, the fiber requirements to produce these volumes are relatively small compared to OSB or plywood. Recent history and base projections of US consumption for these products are shown in Figure 3-1.

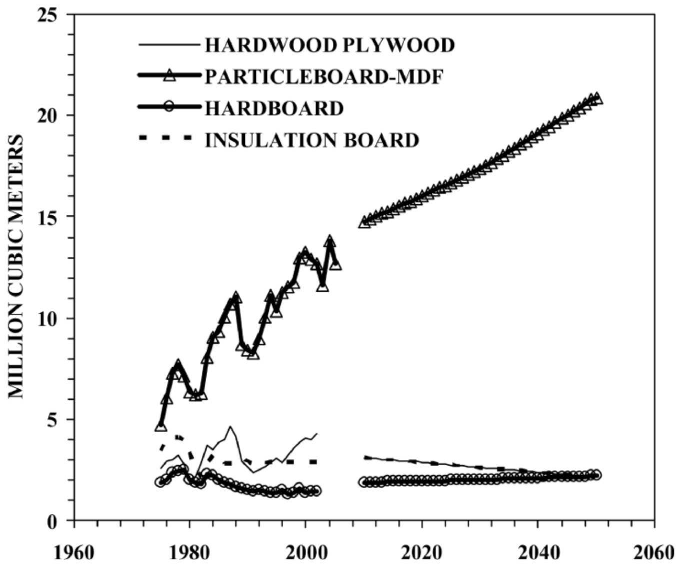

Figure 3-1. US consumption of nonstructural panels, history, and projected base case.

3.3.7 Transport costs

As part of the analysis of spatial equilibrium, TAMM requires estimates of transportation costs associated with the shipment of products from producing to consuming regions. Initial data for these costs were derived from available public and industry association reports on rail and truck shipments. In strictest terms, however, competitive spatial equilibrium requires that goods classed in any given product category (such as softwood lumber) be relatively homogeneous in quality. If this were the case, the difference in supply prices between any two regions shipping to the same demand region would equal the difference in their transport costs to this market. Similarly differences between prices in demand regions served by a given supply region would be no larger than the transport cost differential to the two markets.

For most of the products treated in TAMM, however, the quality mix of production does vary across regions. At the same time, TAMM employs a high level of product aggregation and regional prices are volume-weighted averages across all quality classes. Thus, apart from any other deviations of real-world markets from the competitive ideal,

differences between the average regional supply prices for any two regions serving a given market may depart from the average transport cost differential. This is but one of many examples of the quality aggregation problem discussed by Brooks (1987). In TAMM projections, we have adjusted average interregional transport costs to preserve observed average price differentials at the supply region level.

3.4 MODEL SOLUTION

For a given year, the TAMM model comprises the following blocks of relations:

1. Product demand by region and product (interdependent in product prices) (3.11) and (3.13)
2. Product supply by US and Canadian region (3.23)
3. Offshore softwood lumber supply (Sect. 3.3.3.3)
4. Product market balance by product (demand $\leq$ receipts, supply $\geq$ shipments)
5. Product capacity constraints (output $\leq$ capacity)
6. Stumpage demand by product and region (3.26)
7. Private stumpage supply in the USA and delivered log relations in Canada (Sect. 3.3.5.2)
8. Stumpage market balance (wood use $\leq$ harvest)
9. Harvest volume constraints (harvest $\leq$ available inventory volume)

Between periods, the capacity–investment relations modify production-capacity levels that both bound output and shift the product–supply relations. Endogenous variables include (1) production and demand volumes and prices for supply and demand regions; (2) bilateral product flows between regions; (3) private sawtimber-stumpage supply, total stumpage demand, and sawtimber-stumpage price by supply region; and (4) production-capacity levels by product and supply region.

3.4.1 Market equilibrium

If the nine groups of relations above satisfied the regularity conditions for multiproduct spatial equilibrium outlined by Takayama and Judge (pp114–116 in 1971), single-period market equilibrium solutions for a system of this sort could be obtained by using the approach described by Samuelson (1952). The equilibrium quantities would be

those that maximized the sum of producers' plus consumers' surpluses less transport costs subject to whatever special restrictions might characterize the specific market problem (such as capacity bounds or flow limits). In the present case, however, the product demand functions are not symmetric in cross-price partials (they fail Takayama and Judge's condition 6.2.12). As Takayama and Judge (1971) point out, this does not preclude the existence of a spatial equilibrium. But since the demand functions are not integrable, we can not maximize the sum of producers' and consumers' surpluses because the surpluses are not invariant to the order of integration (across product quantities).

We adopt instead Takayama and Judge's (1971) "net revenue maximization" approach as elaborated by Martin (1981). This involves two steps:

(1) The initial problem is formulated so as to maximize "net revenue", defined as the sum over all the product markets of total consumer payments (price × quantity) less producer variable costs less transport costs. Like the consumers' plus producers' surplus objective, net revenue here has no necessary welfare or market structure interpretation. It is simply a device to drive the market trading process. This formulation will not provide a competitive equilibrium solution, however, because the optimal demand prices will be determined by the marginal revenue curves (rather than the demand curves) and the supply prices by the derivatives of total variable costs (rather than the original supply curves).[8] An example of the primal problem for a simplified version of the TAMM model is shown in Table 3-5. The activities are D_j, S_i, s_i, and T_{ij}, the demand, product supply, stumpage supply, and product shipment volumes, respectively.

(2) To emulate a competitive market solution, we must constrain the net revenue model to impose all of the necessary conditions for spatial equilibrium. The dual of the problem in Table 3-5 is shown in Table 3-6. The activities are $PD_j^*, PS_i^*, PK_i^*, ps_i^*$, and PI_i^*, the equilibrium demand, supply, capacity shadow, stumpage, and inventory shadow prices, respectively. The constraints force precisely the relationship between these equilibrium prices and the prices derived from the original demand and supply curves needed for spatial equilibrium (Martin 1981).

[8] See Martin (p. 41 in 1981) for a demonstration in the quadratic case.

Table 3-5. The primal net revenue maximization problem

Product demand	Product supply	Stumpage supply	Transfers		Right-hand side variable		Equation
$\sum_j PD_j D_j$	$-\sum_i PS_i S_i$	$-\sum_j ps_i s_i$	$-\sum_j \sum_j C_{ij} T_{ij}$				Objective
D_j			$-\sum_i T_{ij}$	$\leq$	EM_j	Exogenous imports	Demand balance
	$-S_i$		$+\sum_j T_{ij}$	$\leq$	$-EX_i$	Exogenous exports	Supply balance
	S_i			$\leq$	K_i	Capacity	Capacity bound
	$r_i S_i$	$-s_i$		$\leq$	XC_i	Exogenous harvest	Stumpage balance
		s_i		$\leq$	I_i	Available inventory	Inventory bound

Definitions: D, S, T, and s are, respectively, demand, supply, transport, and stumpage quantities. PD, PS, and ps are the prices of demand, supply, and stumpage and are the inverse demand, supply, and stumpage supply functions that depend on activities D, S, and s, respectively. Subscripts i and j refer to supply region i and demand region j. r_i is the inverse product recovery factor (input/output).

Table 3-6. Dual of the net revenue maximization problem

Demand balance	Supply balance	Capacity bound	Stumpage balance	Inventory bound	Right-hand side variable		Equation
$\sum_j EM_j PD^*{}_j$	$-\sum_i EX_i PS^*{}_i$	$+\sum_j K_i PK^*{}_i$	$+\sum_i XC_i ps^*{}_i$	$+\sum_i I_i PI^*{}_i$			Objective
$PD^*{}_j$					$\geq PD_j$	Original demand price	Demand price balance
	$-PS^*{}_i$	$+PK^*{}_i$	$+r_i ps^*{}_i$		$\geq -PS_i$	Original supply price	Supply price balance
			$-ps^*{}_i$	$+PI^*{}_i$	$\geq -ps_i$	Original stumpage price	Stumpage price balance
$-PD^*{}_j$	$+PS_i$				$\geq -C_{ij}$	Transfer cost	Demand–supply price balance

Definitions: PD^*, PS^*, and ps^* are the spatial equilibrium prices of demand, supply, and stumpage, respectively. PK^*, PI^* are the equilibrium shadow prices of capacity and inventory. Other variables and functions as defined in Table 3-5.

Once these steps have been completed, the primal-dual problem can be formed by subtracting the dual objective from the primal function and imposing both the primal and the dual constraints. This is shown in Table 3-7. Solution to this problem will meet all of the conditions for spatial equilibrium but will not be soluble because the functions PD_i are still not integrable. To resolve this problem, we force symmetry on the PD_i by replacing them with the functions $\overline{PD_i}$ in which the nonsymmetric pairs of cross-price partials are arbitrarily set equal to the average of the original values. This new objective will not track the original demand structure but the equilibrium prices will lie on the original demand functions because we do not alter the form of PD_i in the demand price constraints in Table 3-7.

The objective function of this new problem is nonlinear (quadratic) in the D_j, S_i, and s_i because of the total revenue terms for product demand, product supply, and stumpage supply. Solutions are obtained in TAMM directly in nonlinear form using the MINOS solver in GAMS (GAMS Development Corporation 2005). The quadratic terms could also be approximated with linear segments (see the solution procedure for the pulp and paper model in Chap. 4) and the problem could be solved by using linear programming.

3.4.2 Links to other model elements

Between annual equilibrium solutions, the model updates three critical links (see further discussion of solution methods in Chap. 8).

(1) Links to other elements of the solid wood model. Production capacity is computed for each solid wood product in each region using the methods described in equations (3.24) and (3.25). The revised capacities act as bounds on output in the following period's market solution and as shifters in the product supply equations.

(2) Links between solid wood and the pulp and paper sector. Prices of residues and pulpwood found in the pulp and paper model (Chap. 4) enter the solid wood sector in the computation of revenues in the product supply equations (3.23) and as shifters for sawtimber supply (3.31), respectively. These prices are also updated between annual solid wood market solutions, since the pulp and paper market equilibrium is computed first in the

Table 3-7. TAMM solution tableau for case of asymmetric cross-price partials in demand: the primal-dual net revenue approach (variable definitions below). Product subscripts and summations omitted

	Product demand	Product supply	Stumpage supply	Transport costs	Equilibrium demand price	Equilibrium supply price	Shadow price capacity	Shadow price inventory	Equilibrium stumpage price	Right-hand side and description	
Objective: net revenue	$\sum_j \overline{PD}_j D_j$	$-\sum_i PS_i S_i$	$-\sum_i ps_i s_i$	$-\sum_i \sum_j C_{ij} T_{ij}$	$-\sum_j PD^*{}_j EM_j$	$+\sum_i PS^*{}_i EX_i$	$-\sum_i PK^*{}_i K_i$	$-\sum_i PI^*{}_i I_i$	$\sum_i ps^*{}_i XC_i$		
Product demand balance	D_j			$-\sum_i T_{ij}$						$\leq EM_j$	Exogenous product imports
Product supply balance		$-S_i$		$+\sum_j T_{ij}$						$\leq -EX_i$	Exogenous product exports
Product supply capacity		S_i								$\leq K_i$	Capacity
Stumpage market balance		$r_i S_i$	$-s_i$							$\leq XC_i$	Exogenous cut
Harvestable volume limit			s_i							$\leq I_i$	Available inventory inventory
Demand price	$-PD_j$				$PD^*{}_j$					≥ 0	
Supply price		PS_i				$-PS^*{}_i$	$PK^*{}_i$		$r_i ps^*{}_i$	≥ 0	
Stumpage price			ps_i					$PI^*{}_i$	$-ps^*{}_i$	≥ 0	
Demand–supply price difference					$-PD^*{}_j$	$PS^*{}_i$				$\geq -C_{ij}$	Transport cost

Definitions: D, S, T and s are, respectively, demand, supply, transport, and stumpage quantities. PD (and $\overline{PD}$), PS, and ps are the prices of demand, supply, and stumpage and are functions of activities D, S, and s, respectively. Subscripts i and j refer to supply region i and demand region j. PD^*, PS^*, PK^*, PI^*, and ps^* are the spatial equilibrium prices of demand, supply, capacity, inventory, and stumpage, respectively, and r_i is the product recovery factor. Explicit endogenous variables are D, S, s, T and PD, PS^*, ps^*, PK^* and PI^*.

Note: The functions $\overline{PD}$, of factor demand curves, are adjusted as described in the text to render symmetric their cross-price partial derivatives of endogenous products. The functions PD are not adjusted but appear in their original asymmetric form.

overall solution process for the projection system (see Chap. 8 for full discussion). Residue volumes available from solid wood processing facilities and sawtimber stumpage prices are passed to the pulp and paper sector where they act as bounds on potential residue consumption at pulp mills and as shifters for the pulpwood stumpage supply equations.

(3) Links between timber harvest and inventory. The private sawtimber-stumpage supply relations in TAMM require inventory volumes updated for harvest and growth. This link presents some difficulties because of the difference in time steps used in the market models (both TAMM and NAPAP are annual) and the ATLAS timber inventory model (which uses 5- or 10-year periods depending on the region, see Chap. 6). To accommodate this difference, TAMM includes a simple linear growth-drain equation that provides inventory estimates in years between ATLAS updates:

$$
\begin{aligned}
INVENTORY_t = {} & INVENTORY_{t-1} \\
& + GROWTH_t - HARVEST_t
\end{aligned}
\tag{3.32}
$$

Harvest is known directly from TAMM/NAPAP, but growth varies over time with residual growing stock, changes in management inputs, and variations in the timberland base. Growth is an endogenous element of the overall Timber Assessment Projection System and can not be known in advance of a model run. As a consequence, an iterative procedure is required to produce a model solution. An initial 50-year full model projection is made with an estimate of growth. The resulting projected time series of growth by region and owner are then substituted into a second full model projection. This process is continued, substituting revised growth estimates in the growth-drain model, until changes in these values fall within a small tolerance between iterations. In regions where timberland area and/or the aggregate level of management intensity can vary markedly between periods, growth of the inventory will also vary significantly over time. In light of this behavior, we have found that an iterative process in which the entire 50-year sequence of growth values is transferred from one iteration to the next leads to the most rapid convergence. In most cases, three to four iterations have been required to meet convergence criteria.

3.5 REVIEW OF APPROACHES TO MODELING THE SOLID WOOD SECTOR

Roundwood used for solid wood products comprised the largest part of global industrial roundwood output in 2004 (about 68%) with some variation by region as noted in the following tabulation:

Industrial roundwood production used for solid wood products by region, 2004[9]

	%
World	68
Asia	80
European Union (25 countries)	73
North America developed	73

Given this importance, there have been numerous studies to model and project future developments for solid wood markets across many regions. From a modeling perspective, these markets differ from those for paper and paperboard in that (1) recovered and intermediate products (such as recycled paper and market pulp) are less important, and hence wood flows in the production stream are less complex; (2) there are often large numbers of solid wood processing firms in a given market with a wide range of output capacities and production efficiencies; and (3) unit capacity costs are less than for pulp and paper mills, lowering barriers to entry, and making it more likely that the appropriate market structure is competitive rather than oligopolistic.

Solberg and Moiseyev (1997) provide a comprehensive survey of past modeling efforts for solid wood products in Europe through the mid-1990s, and several chapters in Yoshimoto and Yukutake (1999) present summaries for key countries in the Asia-Pacific and North American regions. A global overview for earlier periods can be found

[9] Source: FAO Statistics
http://www.fao.org/es/ess/yearbook/vol_1_1/pdf/ b.10.pdf. Roundwood used for solid wood products is defined as sum of saw and veneer logs plus wood-based panels less plywood and veneer sheets. This is an underestimate to the extent that we do not account for recovery loss in plywood and veneer manufacture.

in chapters in Kallio et al. (1987). The remainder of this chapter offers a synthesis of some of the major differences in recent models of solid wood markets.

3.5.1 Short-term models versus long-term models

Perhaps the most fundamental distinction among past modeling approaches is the temporal span or focus of the model. Short-term models deal with time intervals in which price and volume adjustments to changing production, consumption, and trade conditions dominate behavior. In this context, it is unreasonable to treat markets as if they reach some simple balance between aggregate production and consumption quantities. Instead producers are seen as adjusting multiple product flows (production and shipments), consumer demands for products have a critical time dimension (unfilled orders from previous periods and new orders placed in the current period), and stocks of product held by both producers and consumers are significant relative to total output or use.

From a practical perspective, making decisions about these multiple product flows and stocks (and prices) is how solid wood producers and consumers actually operate. Yet, in general, theoretical economic developments on which to base specification of short-term market models are extremely limited. As a consequence, studies of short-term behavior are commonly forced to focus on the predictive ability of the model as justification for a particular specification, identify explanatory variables through ad hoc arguments, or employ statistical methods for isolating causality and linkages (cointegration analysis in recent work). As Hänninen (2004) argued, these studies are on the cutting edge of modern market modeling, trying to find tools that will, in a sense, aid market agents in their day-to-day decisions.

One of the earliest well-documented short-term models of solid wood markets was the quarterly Data Resources Incorporated model in the USA described by Veltkamp et al. (1983) with specific (ad hoc) relations explaining production, shipments, classes of orders, stocks, and prices for softwood lumber and plywood. Lewandrowski et al. (1994) provides a further case—one partly at variance with our above assertion—in which specification of relations explaining monthly shipments, production, and price was partially based on an explicit theory

of short-term adjustment.[10] Producers are seen as expected present-value maximizers of revenues net of costs of production and of explicit costs for inventory holding, which vary directly with the difference between inventory and shipments. This intertemporal optimization (coupled with an added demand relation and generation of expected future price via an ARIMA model) leads to a simple simultaneous equations system for shipments (demand), price (inverse supply), and production with no lags in the endogenous variables.

A more recent example is the Finnish MESU system described using an example by Hetemäki et al. (2004). The basic idea is to focus on key flows in the Finnish forest sector, identifying relations that have good forecasting performance using a mix of basic (long-term) theory for initial specification guidance and statistical methods to determine the final model specification and lag structure. Unlike classical structural approaches, the concerns here are with forecasting potential and not with estimated values of (price or quantity) elasticities. In their example, Hetemäki et al. (2004) consider monthly total German demand for lumber imports, Finnish lumber exports (depending in part on total German import demand), and Finnish sawlog demand (depending in part on Finnish lumber exports), comparing simple ARIMA, structural, vector autoregressive, and error correction approaches.

The largest numbers of past studies, however, have developed long-term models, like the TAMM structure discussed above, based on the classic model of competitive market equilibrium. Wibe (2005) describes the canonical case of this model in its spatial form. The demand quantity is related to production via the apparent consumption identity (possibly modified for inventory change) with price adjusting to affect the balance. Other flows or stocks are ignored or, given the length of the observation period, may differ only modestly from the basic production and consumption volumes or show very limited variation. For example, in the US softwood lumber market, the difference between mill production and shipments may be large from month to month but is quite limited over the course of a year. Change in mill inventory on an annual basis is extremely small relative to total output, as are changes in unfilled orders relative to total consumption.

[10] Producer inventory is also explained by the usual identity involving production, shipments, and start of period inventory.

In contrast, input and output adjustment processes need not be explicitly or separately specified in intertemporal optimization models. For example, in the TSM model (Sedjo and Lyon 1990) and in FASOM (Adams et al. 1996) investment in timber management activities is included as one of the costs of supply in the present value objective with constraints describing the impacts of investments on timber growth. Optimal intertemporal investment patterns are determined together with harvest volumes as part of the consumer plus producer surplus maximization. A similar process is employed to determine lumber production capacity investment in Adams and Latta (2005) where capacity acts as a shifter of timber demand curves and as a bound on timber consumption. In these cases, the extent and timing of adjustments will reflect perfect knowledge of all future market conditions, though constraints can be added to force the model to better mimic observed market behavior.

3.5.2 Specification of demand

Demand relations in past studies of solid wood products have most frequently taken the form of conditional factor demand curves.[11] The end-uses of the solid wood products (housing, furniture, upkeep and remodeling, etc.) are themselves seen as producer goods that use solid wood products as inputs. End-use producers are treated as cost minimizers, so the demand relations include some measure or measures of end-use output(s), including housing activity, manufacturing production, upkeep and remodeling expenditures, or gross domestic product (GDP). These outputs are almost always treated as exogenous. Examples in long-term models include Tachibana and Nagata's (1999) analysis of Japanese plywood markets and some of the sawnwood models described in Lindal's (1997) summary of Danish market studies. Lewandrowski et al. (1994) provide an application in a short-term (monthly) model of domestic US lumber and Hetemäki et al. (2004) in a monthly model of German lumber import demand. An alternative would be to view end-use producers as profit maximizers, yielding unconditional factor demand relations that depend solely on product and factor prices (and levels of any quasi-fixed inputs). We could find

[11] Baudin and Solberg (1989) describe a two-step process of writing the conditional factor demand relations as functions of consumer income by substituting consumer final demand relations for end-use sector output. See also discussion in Adams et al. (1992).

no recent examples of this approach probably because it has lower explanatory power than the conditional form.

Most studies of demand in solid wood markets also recognize some form of price-based substitution between solid wood and nonwood products (e.g. metal framing, gypsum wall sheathing, metal or plastic siding, plastic pallets). Sometimes substitute price measures are highly aggregated (such as an all commodity price index representing the price of "all other goods") and may be used as a general "deflator" for other prices in the relation (as would be consistent, for example, with a normalized quadratic cost function) as in Myneni et al. (1994) and Manurung and Buongiorno (1997). The TAMM approach using composite inputs described above involves prices that are weighted aggregates of both materials and labor inputs for the wood and substitute goods.

Numerous studies also consider price-based substitution between qualities or grades of a given type of solid wood product, for example between species of lumber in a domestic demand analysis (e.g. Lewandroski et al. 1994) or lumber from different countries in a trade study (e.g. Bernard et al. 1997, in a study of Canadian–US lumber trade where prices differ by species and country). It is less common, however, to find explicit treatment of price-based substitution between classes of solid wood products (such as between lumber and panels, between types of panels, or between lumber and laminated veneer lumber or I-joists in construction) although this type of substitution can be important. This is a key part of the solid wood demand structure in TAMM and has also been examined by Baudin and Solberg (1989) in Norway.

3.5.3 Supply-side specification, log demand, and capital stock

Solid wood products supply in forest sector models has been represented by both activity analysis formulations and econometric supply relations. The Norwegian NTMII model described by Bolkesjø et al. (2005) provides an example of the activity analysis approach. In these models, input use is governed by a set of input/output coefficients, multiple production technology options may be available (in some models), and output in total or from a given technology may be limited by capacity. Log or stumpage input demand is a direct conversion of product output.

Other studies use a basic supply equation, expressing output as a function of product and variable factor prices and measures of any quasi-fixed factors (e.g. Bigsby 1993 for Australian lumber, Manurung and Buongiorno 1997 for Indonesian sawnwood and plywood, Tachibana 2000 for Japanese plywood, and Wear and Murray 2004 for US softwood lumber). In some cases, the product supply relation is derived from a profit function analysis of the industry, but in most instances product supply is estimated independently (or possibly in concert with a log demand relation usually without symmetry restrictions). Studies using supply equations may represent the derived demand for logs as a simple fixed coefficients conversion (e.g. Manurung and Buongiorno 1997) or as a separate, price-sensitive log demand equation (as in Tachibana and Nagata 1999), though these approaches may not be fully consistent with the underlying technology assumptions used in developing the product supply relations. In the TAMM model, wood and other inputs are assumed to be weakly separable in production and the wood-use technology is explicitly fixed coefficients. This leads to a fairly unique form for the product supply relations (as discussed in Sect. 3.3.3).

Capital stock or some proxy is a critical part of econometric studies of production behavior in the solid wood sector (see e.g. Abt 1987 for the USA, Latta and Adams 2000 for Canada, and Størdal and Baardsen 2002 for Norway). In sector models, however, studies that use supply relations rather than an activity analysis form do not always include a capital stock or capital price measure (e.g. Wear and Murray 2004). In TAMM and some other models using supply equations, capital stock, or the upper bound on the flow of capital services is represented by production capacity (as opposed to some real dollar value measure of the stock). Capacity, in these cases, enters the model as a supply shifter and also as a limit on output. Changes in capacity (capital stock) over time due to investment, depreciation and retirement are represented by a separate intertemporal adjustment process.[12] In many activity analysis models, although capital stock does not directly enter as a variable input, production capacity is recognized as an output limit with some adjustment processes over time.

[12] The capital stock adjustment process could also be estimated directly with the parameters of the profit function in a so-called "third generation" profit function approach (see, for example, Stevens 1995), but this has not been frequently attempted.

In both approaches (supply equations or activity analysis), capacity is endogenous but the stock that shifts and/or bounds supply is the stock at the start of the period. As a result the capacity adjustment computations take place between annual or periodic market equilibrium solutions in a recursive fashion. Although the adjustment process can take several forms, it generally involves a comparison of the expected profitability of a capacity investment to its cost (or a profit target in TAMM) as outlined in Section 3.3.3.2. Expectations are based on some distributed lag in prices and costs. Sector models that employ an intertemporal optimization format make this process explicit. Discounted capacity cost directly enters the intertemporal objective function, so investment is scheduled over time to make the optimum contribution.

3.5.4 Spatial structure and trade

Forest sector models employ a broad array of spatial structures to model product flows among regions and the establishment of prices in solid wood markets. Adams and Haynes (1987) give a general summary of forms in long-term structural models that solve for the equilibrium between supply and demand. The specific structure depends in part on the number of flows that need to be explained, the degree of competition in the market, and variation in product quality among flows. Relatively simple models may employ an essentially nonspatial structure, with domestic demand and supply relations and a rest-of-world net import or export equation. More complex models may have specific relations for an array of bilateral flows to or from the home country or region. Prices associated with the flows in this latter case may be the same for all flows, or there may be separate demand relations and prices for each flow. This would be appropriate if qualities differed markedly across the flows. Structures of these types tend to be applied to long-term models and can all be solved as simultaneous equations systems. Short-term models, in contrast, such as the Finnish MESU system do not seek to explain equilibrium behavior and generally have one relation for each product flow of interest (Hetemäki et al. 2004).

A spatial equilibrium (SE) structure may be employed where quality differences can be (or are) ignored, there are several flows to track (hence specific equations for each flow would be burdensome), and markets can be assumed to be strongly competitive. TAMM,

NTMII (Bolkesjø et al. 2005), and the GFPM, EFI-GTM, and CGTM (Cintrafor Global Trade Model) models (Cardellichio et al. 1988, 1989; Buongiorno et al. 2003; Kallio et al. 2004) are examples here. In an SE solution, when a bilateral trade flow is positive the profits on that trade arc are zero.[13] There are no trade flows where the profits are negative. Demand and supply region prices differ by no more than the intervening transport cost, and prices between supply regions that trade with the same demand region differ by no more than the difference in their transport costs to that demand region. These are strong conditions, and it is not uncommon to find that the trade pattern suggested by a SE solution differs from the real-world pattern, particularly for smaller flows. In some cases these errors are reduced by imposing flow constraints. The speed of deviation from historical flow patterns may also be controlled by imposing "inertia" constraints that limit the rate at which patterns can evolve.

3.5.5 Sawtimber supply

Private timber supply behavior is extensively studied in the Nordic countries, due to the importance of NIPF ownership in that region. The EFI European modeling compendium by Solberg and Moiseyev (1997) includes summaries by Ronnila, Linddal, Solberg, and Baudin of work through the mid-1990s in Finland, Denmark, Norway, and Sweden, respectively. Based primarily on theories of intertemporal utility maximization (see discussion of TAMM's NIPF approach above), these studies generally relate harvest to current (and some measure of expected) timber prices, inventory, interest rate, and income from nonforest sources. Inventory represents both the harvestable stock and a proxy for amenity values in these models. Other ownership characteristics found to be important include measures of owner wealth, age, and education; size of holding; harvesting costs (given the predominance of roadside delivery in Scandinavia); earnings from associated agricultural enterprises and any agricultural subsidy programs; and conditions of any regional owner association price agreements. Nordic studies of private supply behavior completed since the Solberg and Moiseyev (1997) report, for example Bolkesjø and

[13] Profits are delivered price minus transport cost minus marginal production cost at source. Trade adjusts between trading pairs until one further unit shipped or received would drive the profit negative.

Baardsen (2002) and Kuuluvainen and Tahvonen (1999), employ theories and empirical equations similar to the earlier studies, although with quite different data sets and econometric approaches.

More recent surveys of private timber supply models in Europe and the USA by Beach et al. (2005) and Pattanayak et al. (2002) find similar tendencies. For example in Beach et al.'s (2005) summary of 19 studies in Europe and the USA, at least half of the studies related private harvest to price, income, growing stock inventory, and size (area) of ownership and at least one-third of the studies also included owner age, quality of the site, and some measure of owner interest in recreation or amenity values in the forest. Private harvest behavior is also important in many parts of the Pacific Rim. In Japan, for example, Tachibana (2000) estimated a domestic log supply relation by using price, inventory, harvesting cost (proxied by logging wages), and a time trend.

In the North American context, significant volumes of timber harvest also come from an array of private groups that hold land almost exclusively for its potential economic returns. We have termed this group "forest industry" in the previous sections of this chapter, but its actual composition is varied and, in recent years, changing fairly rapidly. Some of these owners are integrated to processing (hence forest industry), but a growing segment only owns the timberland, managing it to maximize wealth through returns from timber harvest and appreciation in land price. For these ownerships, we employ a simple intertemporal wealth maximization model (equations 3.27, 3.28, and 3.31 above) based largely on the discrete time analysis of Ovaskainen (1992).

Public ownerships are also important timber suppliers in both the USA and Canada. And like private ownerships, they are highly varied in terms of size of holdings, management objectives, and methods of transferring timber harvesting rights to private firms. In the USA, some studies have lumped public and private harvests together in a composite or aggregate supply relationship (e.g. Wear and Murray 2004). Earlier versions of TAMM (see Adams and Haynes 1996), employed a model of the national forest timber supply process based on work by Adams and Haynes (1989) and Adams et al. (1991) with endogenous sales volume, bid and harvest prices, and harvest volume. With the decline in public harvest after 1990, we now take US public supply from all public ownerships as exogenous. The Canadian public harvest system is somewhat more complex than the US case. Messmer

and Booth (1993) and Williams (1991) have developed preliminary models of these processes.

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